Environ Health Perspect

DOI: 10.1289/EHP2427

Note to readers with disabilities: *EHP* strives to ensure that all journal content is accessible to all readers. However, some figures and Supplemental Material published in *EHP* articles may not conform to 508 standards due to the complexity of the information being presented. If you need assistance accessing journal content, please contact ehp508@niehs.nih.gov. Our staff will work with you to assess and meet your accessibility needs within 3 working days.

Supplemental Material

A Prospective Cohort Study of Adolescents' Memory Performance and Individual Brain Dose of Microwave Radiation from Wireless Communication

Milena Foerster, Arno Thielens, Wout Joseph, Marloes Eeftens, and Martin Röösli

Table of Contents

Figure S2. Forest plots of the meta-analysis over the linear exposure estimates for the brain dose calculated separately for the right side users of the five use groups. Coefficients relate to the change in score per interquartile range of the whole sample RF-EMF dose (953 mJ/kg/day).

References

Derivation of the Cumulative RF-EMF brain gray matter dose

1. Numeric simulations of brain gray matter specific absorption rates (SAR)

This section outlines the methodology used to estimate the specific absorption rate (SAR) in adolescents' brains' grey matter. The SAR quantifies the rate at which radio-frequency power is absorbed in (biological) tissue. This quantity cannot be measured in living subjects and therefore needs to be simulated. These simulations rely on human body models or phantoms obtained using imaging techniques such as magnetic resonance imaging.

In this study, the heterogeneous phantoms Billie and Louis from the 'virtual population' are used to obtain SAR values for female and male adolescents, respectively (Gosselin et al. 2014). Billie is an eleven-years-old girl with a height of 1.49 m and a mass of 34 kg. Louis is a male of fourteen years old with a height of 1.68 m and a mass of 49.7 kg. The human body consists out of different tissues that have different properties seen by electromagnetic waves, so called dielectric properties. These properties depend on the frequency of the electromagnetic waves. The phantoms were assigned dielectric parameters from the Gabriel database (Gabriel et al. 1996) corresponding to the frequencies listed in Table S3.

Near field source modeling

In addition, the source of the RF exposure needs to be modeled for the simulation. In this study, the near field source of exposure, the mobile device, was modeled as a dipole antenna. In each frequency band listed in Table S3 a dipole antennas, was tuned to operate next to the body. These dipole antennas represent the mobile phone in the simulation and their dimensions of the dipole antennas can be found in (Aminzadeh et al. 2016).In total, six dipoles are modeled that resonate and emit at the center frequencies of the frequency bands listed in Table S3.

The following three different exposure situations were modelled for near field sources:

- **Close to the body:** During these simulations, the wireless device is assumed to be in the pocket of trousers. A distance between body and dipole of 1 cm was chosen, with the dipoles aligned to the phantom's sagittal and coronal planes.
- **Close to the ear:** In this exposure scenario, the dipoles are placed at 1 cm from the ear of one of the two phantoms and are rotated over 45° towards the phantom's back in the sagittal plane, which contains the dipoles.
- **Hands free kit:** In this exposure scenario, the dipoles in the 'close to the ear' scenario are translated 20 cm further away from the ear orthogonal to the sagittal plane which contains the dipole in the 'close to ear' scenario.

Numerical simulations using the finite-difference time-domain (FDTD) technique (Taflove and Hagness 2005) with Sim4Life (ZMT, Zürich, Switzerland) were executed to obtain SAR values under the RF exposure conditions listed above.

During each of the simulations, a dipole was fed a harmonic signal of 1 W at its resonance frequency and emitted RF-EMFs which are partially absorbed in the human body models. The simulations are executed until a steady state was reached. The induced electric fields in each location of the grey matter of the phantoms were then extracted and used to calculate the SAR in the phantoms in each exposure scenario. These SAR values were then averaged over the mass of the grey matter of the phantoms. This resulted in a set of 5 (frequencies, Table S2) x 1 (averaging volume, the grey matter) x 2 (phantoms, Billie and Louis) x 3 (exposure conditions) = 30 SAR values, which were used for dose calculations.

The obtained near field SAR-values are normalized to 1 W output power of the dipoles used in the simulations. However, a real source might have another output power. Therefore, the SAR values were multiplied with the output power for respective sources in order to properly rescale them. These output powers were derived from literature (Persson et al. 2012). To obtain the GSM output power we assumed a difference in power control of approximately 23dB to an average UMTS output power of 0.45 mW (Kühn and Kuster 2013; Persson et al. 2012). For WiFi we assumed an average output power of 100 mW with an average duty cycle of 3.5 % assuming 10 % of time watching youtube and 90 % surfing (Joseph et al. 2013; Plets et al. 2015). These values were then averaged over the two phantoms and in the case of GSM also averaged over the two GSM frequencies. The resulting SAR grey matter values are listed in column four of Table S2.

Far field source modeling

The simulations described above are valid for exposure from devices relatively close to the human body. However, subjects are also exposed by sources, which may be devices or a mobile network, further away from the human body. In order to model this exposure, a common technique is to use plane waves incident on a human body model. In this study, we have modelled the far-field exposure and corresponding SAR values using plane-wave-simulations in the FDTD-based simulation software SEMCAD X. These plane waves will have a frequency, an angle of arrival (a direction), an amplitude, and a polarization. Our evaluation covered the frequency range from 50 MHz to 5.2 GHz as we simulated at the following frequencies: 50 MHz, 100 MHz, 450 MHz, 835 MHz, 1450 MHz, 2140 MHz, 2450 MHz, 3500 MHz, and 5200 MHz. The field was incident from 6 sides of the body: top, bottom, front, back, left, and right in two mutually orthogonal polarizations. The simulated human body models under this exposure are Billie and Thelonius from the same virtual population. Thelonius is a six-year-old boy with a mass of 18.6 kg and a height of 1.16 m. The Louis model was not available in this configuration.

The simulations result in specific absorption rate values (SAR) in the grey matter of these two phantoms. These SAR values are averaged over the grey matter of the phantoms. For each phantom and each frequency, 12 SAR values are extracted corresponding to the six directions of incidence and two orthogonal polarizations. These SAR values correspond to an incident electric field strength of 2.45 V/m, which is chosen in the simulation. They are renormalized to mean incident field strengths, see Table S2, obtained using geospatial propagation models (Bürgi et al, 2010).The SAR values are then averaged over these 12 values, the two phantoms, and interpolated to the centre frequencies of the respective telecommunication frequency band. The resulting values are listed in Table S2 for far-field exposure.

2. Usage variable overview

Table S1: Derivation of the individual durations of near field exposure situations and mean incidence fields of environmental far field sources

RF-EMF near field source	Source	Derivation for estimated variables
Mobile phone calls		
Daily duration (min/day)	- HERMES questionnaire - Operator recorded data	Estimated via multilevel linear regression modeling with the school as cluster variable calibrated on the objectively recorded cumulative operator data call duration per day. Variables from the HERMES questionnaires were stepwise included in order to determine the best fitting model. The predicted values from the model were used for further data analysis as estimated cumulative daily call duration for all participants without operator data records. The following predictors were used in the final model - Age - Gender - Difference in daily duration of mobile phone calls (follow-up-baseline) - Daily frequency of mobile phone calls at follow-up - Daily frequency of messages per day at follow-up - Daily duration of mobile phone data traffic at follow-up - Daily duration of DECT phone calls at follow-up
Network proportion (%)	- HERMES questionnaire - Operator recorded data - Propagation model	RF-EMF exposure is strongly related to the network used for calling. During the HERMES study the GSM and the UMTS network were used in Switzerland. The proportion of UMTS was estimated via multilevel linear regression modeling with the school as cluster variable calibrated on the operator recorded UMTS proportion. Variables from the HERMES questionnaires were stepwise included in order to determine the best fitting model. The predicted values from the model were used for further data analysis as estimated proportion of UMTS for all participants without operator data records. The proportion of GSM was subsequently assumed to be 1-proportion(UMTS). The following predictors were used in the final model - Place of residence (urban vs. rural) - Far field UMTS-proportion of modeled mobile phone downlink - Number of smartphones at home - Daily duration of mobile phone data traffic
Headset use (%)	- HERMES questionnaire	The answer categories “never”, “seldom”, “often” and “most of the time/always” were translated to the numerical values 0, 0.25, 0.50 and 1, respectively, and furthermore averaged over baseline and follow-up.
Mobile phone data traffic		
Daily duration (min/day)	-HERMES questionnaire	
Proportion 3G /WiFi (%)		
Mobile phone close to body; (min/day)		Exposure to RF-EMF only while the mobile phone is actively transmitting or sending data (receiving a message, connecting to a mobile phone antenna) or receiving a call. This actual exposure time to be assumed 1 % of total time on body
Landline phone calls (DECT)		
Daily duration (min/day)	- HERMES questionnaire	
Eco mode (yes/no)		
Computer, laptop and tablet use with WiFi		
Daily duration use (min/day)	- HERMES questionnaire	
Proportion of WiFi connection (%)		

Table S1 continued

RF-EMF far field source [a]	**Source**	**Derivation of estimated variables**
Uplink (from other people)	-Personal RF-EMF measurements - HERMES questionnaire	Estimated via multivariable linear regression modeling calibrated on the mobile phone uplink obtained via personal RF-EMF measurements of 148 participants. Variables from the self-reported baseline questionnaire were stepwise included in order to determine the best fitting model. Subsequently the predicted values from the model were used as uplink estimates for dose calculation for all participants without personal measurement data. The following predictors were used in the final model - Mobile phone operator - Mobile phone on/off during night - Number of Smartphones at home - Daily duration using public transport: train - Daily duration using public transport: bus - Investigation phase (2012-3014 vs. 2014-2016)
Downlink GSM900	- Propagation model	Described in Bürgi et al, 2010
Downlink GSM1800		
Downlink UMTS		
WiFi	-Personal RF-EMF measurements - HERMES questionnaire	Estimated via multivariable linear regression modeling calibrated on the WiFi band obtained via personal RF-EMF measurements of 148 participants. Variables from the self-reported baseline questionnaire were stepwise included in in order to determine the best fitting model. Subsequently the predicted values from the model were used as WiFi estimates for dose calculation for all participants without personal measurement data. The following predictors were used in the final model - Mobile phone operator - WiFi at school - Daily duration of mobile data traffic - Investigation phase (2012-3014 vs. 2014-2016)
DECT	-Personal RF-EMF measurements	Mean far field exposure for the DECT frequency derived from the personal measurements conducted with 148 participants
TV	- Propagation model	Described in Bürgi et al, 2010
Radio/Broadcast		

[a] Adolescents far-field exposure in school might differed from far-field exposure at home. Adolescents' time in school was assumed to be one fifth of 24 hours on weekdays and modelled values from the place of school were used for this proportion of time. Further far-field exposure might be substantially higher in public transports than elsewhere due to the many people actively engaged with their mobile phones. Average times spent in public transports were derived from personal measurements or the questionnaire. The remaining time neither spent in school nor in public transports was assumed residential time at home.

3. Overview of the parameters considered for RF-EMF brain gray matter dose

Table S2: Parameters used for the derivation of the cumulative near field dose. Individual exposure to a source is calculated via multiplying the individual time per exposure scenario with its respective SAR value. The brain and whole body dose is consecutively calculated as the sum of the individual exposure of the near-field sources. The table below summarizes the mean values used for the individual RF-EMF dose calculation for all HERMES participants who took part in baseline and follow-up investigations. Note that the duration refers to the average daily device use between baseline and follow-up

RF-EMF near field source	**N**	**Mean duration sec / day (SD)**	**Brain SAR (mW/kg)**	**Average dose contribution (%)**
Mobile phone calls				
GSM mobile phone calls without headset [a]	844	107 ± 153	6.24	79.79
GSM mobile phone calls with headset [a]	844	22 ± 57	0.75	
UMTS mobile phone calls without headset	844	140 ± 383	0.03	0.45
UMTS mobile phone calls with headset	844	33 ± 112	$4*10^{-3}$	
Mobile phone data traffic				
Via mobile internet connection	843	743 ± 980	$7*10^{-5}$	1.82
Via WiFi	843	2590 ± 1846	$2*10^{-5}$	3.44
Mobile phone close to body (passive mobile phone data traffic)	843	192 ± 166	$2*10^{-5}$	0.25
Cordless phone calls (DECT)				
With eco mode	766	373 ± 398	0.61	
Without eco mode	77		0.06	8.29
Computer, laptop and tablet use with WiFi	843	2602 ± 3329	$2*10^{-5}$	0.01

RF-EMF far field source	**Mean electric field [V/m]**	**Brain SAR (mW/kg per V/m)**	**Average dose contribution (%)**
Uplink (mobile phone connections from surrounding people)	0.11	$6.5*10^{-3}$	2.02
Downlink GSM900	0.08	$8.2*10^{-3}$	1.45
Downlink GSM1800	0.07	$6.5*10^{-3}$	0.92
Downlink UMTS	0.08	$5.6*10^{-3}$	0.99
WiFi	0.04	$4.6*10^{-3}$	0.24
Radio/Broadcast	0.02	$2.9*10^{-3}$	0.02
TV	0.03	$8.0*10^{-3}$	0.21
DECT	0.01	$6.3*10^{-3}$	0.01

[a] For calls with the mobile phone on the GSM network the mean of the SARs for the GSM900 and the GSM1800 network was used because there was no differentiation between GSM900 and GSM1800 network in the mobile phone operator data. A headset is assumed to be wired to the phone.

Table S3: Simulated RF frequency bands with frequency range and center frequency

RF signal	**Frequency range (MHz)**	**Center frequency (MHz)**
GSM 900-UL	880-915	897
GSM 1800-UL	1710-1785	1748
DECT	1880-1900	1890
UMTS-UL	1920-1980	1950
Wi-Fi 2 GHz	2400-2483.5	2450

Meta-analysis over five latent classes of media use

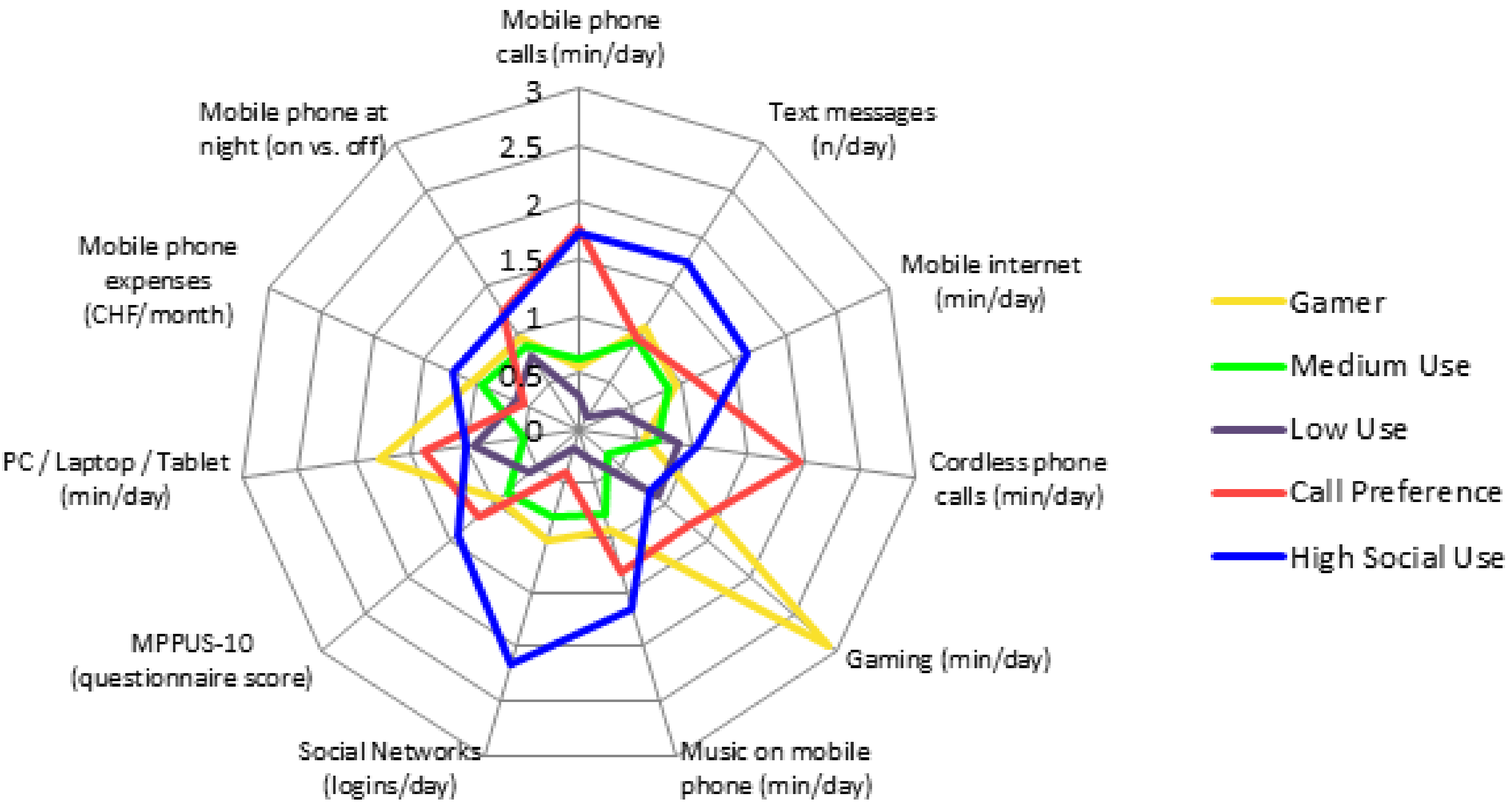

Figure S1: Spider plot displaying the profile of the five different media use patterns (Foerster and Röösli 2017) on 11 different media use variables. Values are relative and relate to the ratio between the group mean and the overall mean of the whole sample on the raw questionnaire scores (e.g. a peak of the “Gaming” group at 3 relates to a three times (300 %) higher daily gaming duration compared to the whole sample whereas a value of 0.5 relates to a 50 % lower value on the respective variable.

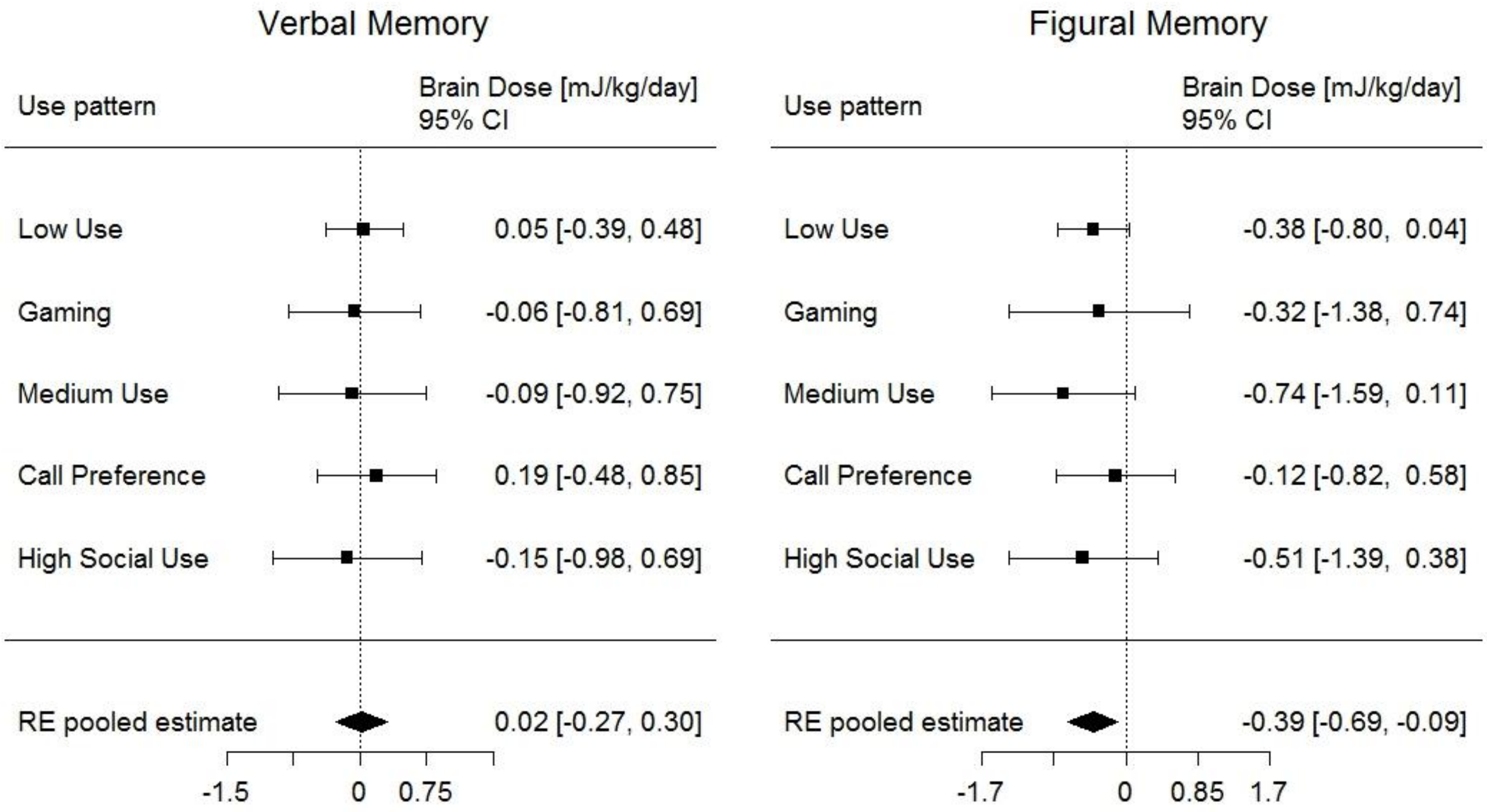

Figure S2: Forest plots of the meta-analysis over the linear exposure estimates for the brain dose calculated separately for the right side users of the five use groups. Coefficients relate to the change in score per interquartile range of the whole sample RF-EMF dose (953 mJ/kg/day).

References

Aminzadeh R, Thielens A, Bamba A, Kone L, Gaillot DP, Lienard M, et al. 2016. On-body calibration and measurements using personal radiofrequency exposimeters in indoor diffuse and specular environments. Bioelectromagnetics 37:298-309.

Bürgi A, Frei P, Theis G, Mohler E, Braun-Fahrländer C, Fröhlich J, et al. 2010. A model for radiofrequency electromagnetic field predictions at outdoor and indoor locations in the context of epidemiological research. Bioelectromagnetics 31:226-236.

Foerster M, Röösli M. 2017. A latent class analysis on adolescents media use and associations with health related quality of life. Computers in Human Behavior 71:266-274.

Gabriel S, Lau R, Gabriel C. 1996. The dielectric properties of biological tissues: Iii. Parametric models for the dielectric spectrum of tissues. Physics in medicine and biology 41:2271.

Gosselin M-C, Neufeld E, Moser H, Huber E, Farcito S, Gerber L, et al. 2014. Development of a new generation of high-resolution anatomical models for medical device evaluation: The virtual population 3.0. Physics in medicine and biology 59:5287.

Joseph W, Pareit D, Vermeeren G, Naudts D, Verloock L, Martens L, et al. 2013. Determination of the duty cycle of wlan for realistic radio frequency electromagnetic field exposure assessment. Progress in Biophysics and Molecular Biology 111:30-36.

Kühn S, Kuster N. 2013. Field evaluation of the human exposure from multiband, multisystem mobile phones. IEEE Transactions on Electromagnetic Compatibility 55:275-287.

Persson T, Törnevik C, Larsson LE, Lovén J. 2012. Output power distributions of terminals in a 3g mobile communication network. Bioelectromagnetics 33:320-325.

Plets D, Joseph W, Vanhecke K, Vermeeren G, Wiart J, Aerts S, et al. 2015. Joint minimization of uplink and downlink whole-body exposure dose in indoor wireless networks. BioMed research international 2015.

Taflove A, Hagness SC. 2005. Computational electrodynamics:Artech house.